Cosmic Collisions and the Longevity of Non-Spacefaring Galactic Civilizations

Steven J. Ostro
303-233 Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, California 91109-8099 USA
818-354-3173, fax -9476, email ostro@echo.jpl.nasa.gov

and

Carl Sagan (deceased)
Cornell University

SUMMARY

Interplanetary collision hazards in many planetary systems force civilizations to become spacefaring or extinct. This selection pressure apparently acts on a timescale of 10^5 years on Earth's current human civilization, but may act on shorter or longer timescales elsewhere.

The absence on Earth and in astronomical data of unambiguous signs of interstellar spacefaring civilizations -- at a time when we ourselves are, with Pioneers 10 and 11 and Voyagers 1 and 2, capable of rudimentary interstellar flight -- has been called the Fermi Paradox (e.g., Shklovskii and Sagan 1966, Brin 1983). Among the explanations offered (see synopses by von Hoerner 1995 and Crawford 1997) are that we are being visited and either can detect the visitors (UFOs, although the evidence is wholly non-compelling) or cannot (the "zoo hypothesis" of Ball 1973); that there are intractable physical or economic impediments to interstellar spaceflight (Purcell 1963; Drake and Sobel 1992); that diffusion limits on interstellar space flight are such that we have not yet been visited (Newman and Sagan 1981); that the evolution of life and technical civilizations is much more improbable than we might guess from our own presence (Hart 1975, Tipler 1980, Sagan and Newman 1983, Diamond 1995); or that even if technical civilizations arise abundantly, they tend to destroy themselves before achieving extensive interstellar spaceflight (Shklovskii and Sagan 1966).

Another possible explanation has over the years been offered (e.g., Ashkenazi 1995): there is no general imperative, it is argued, for intelligent species to invent spaceflight -- even among civilizations that are technologically superior to our own. Only under quite special conditions, it is suggested, will spaceflight develop. An exactly analogous argument can be made regarding radar astronomy and interplanetary radio communications. It is perfectly possible, advocates of these ideas propose, that the Galaxy is filled with highly advanced civilizations that never develop high technology, or that prudently abandon it -- or even that develop high technology but not high-power radar transmitters and not spaceflight. Then we can understand why we have not received radio signals or visits from other civilizations in space.

We argue here that there is a common factor that will drive large numbers of technical civilizations into space, that those civilizations which choose not to become spacefaring will for this very reason be rendered extinct, and that, by a kind of natural selection, all sufficiently long-lived civilizations must be spacefaring (and are likely to have developed radar/ radio techniques).

The Collision Hazard

We now recognize that the Earth orbits the Sun amidst a swarm of comets and asteroids, that impacts of these objects with the Earth are inevitable, and that civilization-threatening impacts should occur on a timescale (i.e., average interval) of 105 to 106 years (Chapman and Morrison 1993, Toon *et al.* 1997). For the Earth, the threshold for catastrophic global effects is the impact of an object of diameter between 1 and 3 km. The kinetic energy of impact, $E = 10^5$ to 10^6 Mt, where 1 Mt = 4.185×10^{15} joules, is so high that a globe-enshrouding stratospheric cloud of impact debris (dust, asteroidal sulfates, and soot from wildfires ignited by the impact's thermal radiation) will lower light levels, drop temperatures, destroy the ozone shield and have many other deleterious effects, especially through the global termination of agriculture. The deaths of a significant fraction of the human population are anticipated. Much lower-energy impacts ($E = 10^4$ to 10^5 Mt, projectile size ~ 500 m, average interval of order 60,000 years) into an ocean could raise tsunamis able to inundate a kilometer of coastal plain over entire ocean basins, killing up to 1% of our population. Much higher-energy impacts ($E > 10^7$ Mt, projectile size of order 10 km, interval > 20 million years) can cause mass extinctions; it is widely thought that the Cretaceous-Tertiary impact of 65 million years ago eliminated at least 60% of Earth's species (Sharpton and Ward 1990, Sheehan and Russell 1994).

We do not argue here about what impact energy threshold would be necessary to wreck global civilization with confidence, what the average interval is between impacts that could render the human species extinct, etc. (Adushkin and Nemchinov 1994). Whatever these numbers are, if we wait long enough, the relevant event will occur.

To deal with the asteroidal component of the terrestrial impact hazard, it is probably sufficient to have interception capabilities restricted to within a few AU of Earth. At their current discovery rate, Earth-based surveillance will locate the entire population of kilometer-sized, possibly hazardous asteroids during the next century or two. Unless we are unlucky enough to suffer a catastrophic collision in the interim, it will be a simple matter to mitigate a civilization-disrupting asteroid collision, because there will be adequate warning time. Means have been suggested for deflecting asteroids into harmless trajectories or, if the warning time is too short, destroying them. In all cases the technical solutions require implanting or attaching devices to the object or exploding nuclear weapons near it (Ahrens and Harris 1992, Melosh *et al.* 1994). It is difficult to imagine practicable means of deflecting which do not require a substantial capability for interplanetary robotic spaceflight. For the shortest-warning-time scenarios, space missions piloted by humans might be required for mitigation of an impending collision, if the advantages of onboard human intelligence outweighs the associated cost and risk.

The odds of a very-long-period comet (LPC) collision in a millennium are similar to odds of an equally energetic asteroid collision in a century, but dealing with the LPC component of the impact hazard is orders of magnitude more challenging. Groundbased and spaceborne reconnaissance of physical properties is intrinsically much more difficult than for asteroids, so deflection or destruction of a threatening LPC would require more exotic weaponry and very much longer warning times than would a threatening asteroid. However, we cannot detect LPCs much more than a few months before their arrival in the inner solar system (Marsden and Steel 1995), because coma-producing evaporation of volatiles by insolation typically doesn't turn on until a comet gets within about Jupiter's distance from the Sun, because even very large (>10 km) inactive nuclei far beyond those distances generally are too dim for VIS/IR telescopic detection, and because LPC motion against the star background is inconspicuous.

Sooner or later human civilization must confront the asteroid/comet collision hazard or become extinct. Dealing with interplanetary collision hazards over a period of centuries or millennia will naturally take our spacefaring society further out into the solar system -- if for nothing else, to improve surveillance of incoming comets. As technology advances and the life-span of our species (and its successors) lengthens, a slow outward transition from interplanetary travel towards cometary source regions and interstellar spaceflight seems conceivable (Sagan 1994). Extraterrestrial Civilizations In the long run, the threat of interplanetary impacts must play a role in the evolution not only of our civilization, but of any others that may have evolved on the planets of other stars with residual small-body populations. The nature of the small-body collision hazard that confronts extraterrestrial civilizations may be very different from ours, depending on such factors as the physical and chemical characteristics of the planet and its biosphere, the biological and sociological nature of the civilization, and of course the collision flux itself. Discs of planetesimals are thought to be a ubiquitous stage in the formation of planetary systems. Our system contains several primordial sub-populations of small bodies that feed potential impactors into Earth-crossing orbits: the main asteroid belt, which supplies near-earth asteroids; the Kuiper Belt, which supplies short-period comets; and the Oort Cloud, which supplies LPCs. Both the existence of the source populations and the mechanisms that maintain Earth's collision flux are, in part, a consequence of the radial distribution of large masses in the solar system, which in turn are an outcome of the initial physical conditions (especially the gas/dust ratio) in the primitive solar nebula (Lunine 1995). For example, our Oort Cloud was probably populated by gravitational ejecta from the Uranus and Neptune regions (Fernandez 1978; Fernandez and Ip 1983). If there are no planets that play the role of Uranus and Neptune in systems otherwise like our own, their Oort Clouds may be very thinly populated or nonexistent, although they may retain densely populated peripheral Kuiper belts. Stars in open and globular clusters, stars closer to the center of the Galaxy, stars experiencing more frequent encounters with Giant Molecular Clouds, may all experience higher impact fluxes at their terrestrial planets, if any. In our system, the main asteroid belt is the remnant of planetesimals that were kept from accumulating into a planet by the disruptive gravitational effect of Jupiter, and Jupiter's mean-motion resonances are the key mechanism for injection of main-belt asteroids into Earth-crossing orbits. On the other hand, Jupiter gravitationally shields the

Earth from LPC impacts; Wetherill (1994) has calculated a 2.5-order-of-magnitude increase in the cometary flux at the Earth had the planet Jupiter never formed. Thus there may be many possibilities for residual small-body populations and the evolution of the impact flux in systems containing Earth-like planets. For example, gas-rich planetary accretion discs might create giant planets in the "wrong" place (Ward 1997), while gas-poor disks may generate terrestrial planets but neither category (Jupiter/Saturn or Uranus/Neptune) of giant planet and hence a negligible impact flux.

Collisions and Creation

Impacts during the first ~ 100 My of Earth's history may have played a role in the origin of life, both in preventing its "permanent" establishment during the post-accretional heavy bombardment (Maher and Stevenson 1988) and in delivery of volatiles and prebiotic organic molecules (Chyba *et al.* 1994). Our Moon, which is thought to formed by the (glancing?) impact of a Mars-sized planetesimal into the proto-Earth (Hartmann and Davis 1975, Cameron and Ward 1976), has prevented fluctuations in Earth's obliquity that would have destabilized the climate and short circuited evolution (Laskar *et al.* 1993, Laskar 1997). High-energy impacts are thought to have caused at least some, if not most, of Earth's mass extinctions (Rampino and Haggerty 1996 and refs. therein) and may have increased the rate of evolution, in the sense of Gould and Eldredge's (1993) punctuated equilibrium. More frequent, lower-energy impacts may have catalyzed the evolution of biological diversity between mass extinction events (Morris 1998).

We conjecture that Earth's rich and complex history of asteroid/comet collisions has accelerated the appearance of intelligent life on our planet, and that the timescale for the evolution of life and the emergence of extraterrestrial technological civilizations depends on the distribution and dynamics of small bodies left over from planet formation. Large impact fluxes might increase the rate of evolution, whereas too high a flux clearly would be inimical to the development of civilization. Conversely, too low a flux might forestall the appearance of intelligent life. In any event, for our single available sample of a technological civilization, the same interplanetary collision flux that may have been instrumental in its creation also constitutes a definite threat to its long-term existence. One consequence of these arguments is that the Galaxy does not contain many civilizations that are both long-lived and have never developed at least a robotic spacefaring capability.

Surveillance Radars and SETI

Likewise, the utility of electromagnetic radiation in controlling spacecraft, in returning data from spacecraft to the home planet, and in studying the nature and trajectories of asteroids and comets, is so high that successful avoidance of the collision hazard without development of radio telemetry and radar remote sensing seems similarly implausible. Currently, laser radars are orders of magnitude less sensitive than planetary radar telescopes. Development of this technology may someday enable laser radars to detect reflections from Earth-crossing asteroids that permit imaging and astrometric measurements as precise as is now achievable with radio-wavelength radars. Similarly, optical telemetry has bandwidth advantages over radio telemetry and soon will be implemented for some NASA missions. However, centimeter and longer wavelengths can be used around the clock and in any weather. They also have fundamental advantages in the physical and dynamical characterization of comet nuclei, whose comas are optically opaque but radio-translucent, and in the assessment of the large-particle component of those comas. Given the paramount importance of high-precision ranging to the nucleus in predicting a comet's trajectory, radio-wavelength radars would seem to be essential to defense against threatening comets (Ostro 1994). A possible implication for SETI is that transmissions from small-body radar astronomy, which often are very narrowband, constitute beacons that might be detectable over galactic distances. Radar astronomy on Earth already contributes the brightest, albeit very intermittent and highly directional, electromagnetic signature of our civilization, and it is likely to become increasingly powerful and less intermittent. The several dozen radar-detected Earth-crossing asteroids are a tiny fraction of the population of objects that are desirable to monitor in order to maintain the accuracy of orbit predictions. Future generations of very sensitive radar telescopes (with very powerful transmitters), perhaps constructed as part of our planet's defense against LPCs, will be able to study enormous numbers of asteroids that are both potentially threatening on long timescales and attractive targets of robotic and piloted space missions on short timescales. Ironically, the population of asteroids that can collide with Earth includes the cheapest destinations for such missions, which might be motivated not just by concern about the collision hazard but also by any of the factors that have driven human exploration in the past. Indeed, given the accessibility and resource potential of near-Earth asteroids (Lewis and Hutson 1993), development of an asteroid orbit-manipulation infrastructure could offer an irresistible return on investment, one of whose spin-offs would be a head start on systems that ultimately will be necessary for planetary defense.

Double-Edged Sword

However, altering the trajectories of objects in nearby interplanetary space can introduce perils on timescales much shorter than the average intervals between natural impact catastrophes (Sagan and Ostro 1994a,b; Harris *et al.* 1994). Thus, interplanetary collision hazards may act as a kind of sieve, simultaneously requiring civilizations to become spacefaring and to institute stringent controls on the misuse of orbit-engineering technology. These joint constraints may or may not be so severe as to truncate the longevity of spacefaring civilizations below the timescales for civilization-ending impacts themselves. One way or another, interplanetary collisions constitute a unique, exogenous environmental factor in the natural selection of long-lived civilizations.

Acknowledgements: Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Work at Cornell was supported in part by NASA Grant NAGW 1896.

REFERENCES

Adushkin, V. V. and Nemchinov, I. V., 1994. Consequences of impacts of cosmic bodies on the surface of the Earth. In *Hazards Due to Comets and Asteroids*, ed Gehrels, T., and Matthews, M. S., Univ. of Arizona Press, Tucson, pp. 721-778.

Ahrens, T. J. and Harris, A. W., 1992. Deflection and fragmentation of near-earth asteroids. *Nature*, **360**, 429-443.

Ashkenazi, M., 1995. Will ETI be space explorers? Some cultural considerations, *Astron. Soc. Pac. Conf. Ser.*, **74**, 507-517.

Ball, J., 1973. The zoo hypothesis. *Icarus*, **19**, 347-349.

Brin, G. D., 1983. The "Great Silence:" The controversy concerning extraterrestrial life. *Q. J. R. Astr. Soc.*, **24**, 283-309.

Cameron, A. G. and W. R. Ward, 1976. The origin of the Moon. In *Lunar Sci. VII*, Houston: Lunar Science Institute, pp. 120-122 (abstract).

Chapman, C. R., and Morrison, D., 1994. Impacts on the Earth by asteroids and comets: Assessing the hazard. *Nature*, **367**, 33-40.

Chyba, C. F., Owen, T. C., and Ip, W.-H., 1994. Impact delivery of volatiles and organic molecules to Earth. In *Hazards Due to Comets and Asteroids*, ed Gehrels, T., and Matthews, M. S., Univ. of Arizona Press, Tucson, pp. 9-58.

Crawford, I. 1997. How common are technological civilizations? *Astronomy and Geophysics* **38:4**, 24-26.

Diamond, J., 1995. Alone in a crowded universe. In *Extraterrestrials: Where Are They?* 2nd, ed Zuckerman, B. and Hart, M. H., Cambridge Univ. Press, pp. 157-164.

Drake, F. D. and Sobel, D., 1992. *Is Anyone Out There?* (Delacorte, New York).

Fernandez, J. A., 1978. Mass removed by the outer planets in the early solar system. *Icarus*, **34**, 173-181.

Fernandez, J. A., and Ip, W.-H., 1983. On the time evolution of the cometary influx in the region of the terrestrial planets. *Icarus*, **54**, 377-387.

Gould, S. J. and Eldredge, N., 1993. Punctuated equilibrium comes of age. *Nature*, **366**, 223-227.

Harris, A. W., Canavan, G. H., Sagan, C. and Ostro, S. J., 1994. The deflection dilemma: Use vs. misuse of technologies for avoiding interplanetary collision hazards. In *Hazards Due to Comets and Asteroids*, ed Gehrels, T., and Matthews, M. S., Univ. of Arizona Press, pp. 1145-1155.

Hart, M., 1978. An explanation for the absence of extraterrestrials on Earth. *Q. J. R. Ast. Soc.*, **16**, 128- 135.

Hartmann, W. K. and Davis, D. R., 1975. Satellite-sized planetesimals and lunar origin. *Icarus,* **24**, 504-515.

Laskar, J., 1997. Large-scale chaos and marginal stability in the solar system. *Celestial Mech. and Dynamical Astronomy,* **64**, 115-162.

Laskar, J., Joutel, F. and Robutel, P., 1993. Stabilization of the Earth's obliquity by the Moon. *Nature,* **361**, 615-617.

Lewis, J. S. and Hutson, M. L., 1993. Asteroidal resource opportunities suggested by meteorite data. In *Resources of Near-Earth Space,* ed J. Lewis,

M. S. Matthews and M. L. Guerrieri, Univ. of Arizona Press, 523-542.
Lunine, J. I., 1995. The frequency of planetary systems in the galaxy. In *Extraterrestrials: Where Are They?* 2nd, ed Zuckerman, B. and Hart, M. H., Cambridge Univ. Press, Cambridge, pp. 192-214.

Maher, K. A., and Stevenson, D. J. 1988. Impact frustration of the origin of life. *Icarus,* **91**, 93-100.

Marsden, B. G. and Steel, D. I., 1994. Warning times and impact probabilities for long-period comets. In *Hazards Due to Comets and Asteroids,* ed Gehrels, T., and Matthews, M. S., Univ. of Arizona Press, Tucson, pp. 221-239.

Melosh, H. J., Nemchinov, I. V. and Zetzer, Yu. I., 1994. Non-nuclear strategies for deflecting comets and asteroids. In *Hazards Due to Comets and Asteroids,* ed Gehrels, T., and Matthews, M. S., Univ. of Arizona Press, Tucson, pp. 1111-1132.

Morris, S., 1998. The evolution of diversity in ancient ecosystems: a review. *Phil. Trans. Royal Soc. London, Series B - Biological Sciences,* **353**, 327-345.

Newman, W. I. and Sagan, C., 1981. Galactic civilizations - Population dynamics and interstellar diffusion. *Icarus,* **46**, 293-327.

Ostro, S. J., 1994. The role of groundbased radar in near-Earth object hazard identification and mitigation. In *Hazards Due to Comets and Asteroids,* ed Gehrels, T., and Matthews, M. S., Univ. of Arizona Press, Tucson, pp. 259-282.

Purcell, E., 1963. *Interstellar Communication,* ed Cameron, A.G.W., W. A. Benjamin, New York.

Rampino, M. R. and Haggerty, B. M. 1996. The "Shiva Hypothesis": Impacts, mass extinctions, and the galaxy. *Earth, Moon, and Planets,* **72**, 441-460.

Sagan, C., 1994. *Pale Blue Dot: A Vision of the Human Future in Space,* Random House, New York.

Sagan, C. and Newman, W. I., 1983. The solipsist approach to extraterrestrial intelligence. *Q. J. R. Astr. Soc.*, **24**, 113-121.

Sagan, C. and Ostro, S. J., 1994a. Dangers of asteroid deflection. *Nature*, **368**, 501.

Sagan, C. and Ostro, S. J., 1994b. Long-range consequences of interplanetary collisions. *Issues in Science and Technology,* **10**, 67-72.

Sharpton, V. L., and Ward, P. D., eds. 1990. *Global Catastrophes in Earth History,* Geol. Soc. Am. Spec. Paper No. 247, Boulder, Colorado.

Sheehan, P. M., and Russell, D. A. 1994. Faunal change following the Cretaceous-Tertiary impact: Using Paleontological data to assess the hazards of impacts. In Hazards Due to Comets and Asteroids, ed Gehrels, T., and Matthews, M. S., Univ. of Arizona Press, Tucson, pp. 879-893.

Shklovskii, I. S. and Sagan, C., 1966. *Intelligent Life in the Universe.* Holden-Day, San Francisco.

Tipler, F. J., 1980. Extraterrestrial intelligent beings do not exist. *Q. J. R. Astr. Soc.* **21**, 267-281.

Toon, O. B., Zahnle, K., Morrison, D., Turco, R. P., and Covey, C, 1997. Environmental perturbations caused by the impacts of asteroids and comets. *Rev. Geophys.*, **35**, 41-78.

von Hoerner, S., 1995. The likelihood of interstellar colonization, and the absence of its evidence. In *Extraterrestrials: Where Are They?* 2nd, ed Zuckerman, B. and Hart, M. H., Cambridge Univ. Press, Cambridge, pp. 29-33.

Ward, W. R., 1997. Survival of planetary systems. *Astrophys. J.* **482**, L211-L214.

Wetherill, G., 1994. Possible consequences of absence of Jupiters in planetary systems. *Astrophysics and Space Sciences*, **212**, 23-32.